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Modelling the electromagnetic scattering by 3-D objects in a layered media

Electromagnetic active detection of metallic targets

Marius S. Birsan

Defence R&D Canada – Atlantic

Technical Memorandum

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The underwater electromagnetic (EM) active detection technique attempts to reveal a stealth iron-hull vessel (submarine or surface warship) located in a horizontal layer of seawater. Our goal is to numerically investigate the EM scattering process in the presence of a metallic vessel of arbitrary shape placed inside a lossy media. To solve the EM scattering problem involving perfectly conducting (PEC) objects we make use of the Method of Moments (MoM) integral equation technique. The EM scattering numerical code was written in Fortran. The solution is applied to the investigation of EM scattering by a submarine modelled as a tapered long cylinder plus the tower when is placed in different positions relative to the source and the sensors. It is shown that, by an appropriate design of the experiment, the signal indicating the presence of the target can be increased relative to the signal obtained in its absence.

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Abstract

The underwater electromagnetic (EM) active detection technique attempts to reveal a stealth iron-hull vessel (submarine or surface warship) located in a horizontal layer of seawater. It is supposed that the vessel has no signature, acoustic or electromagnetic, and the only way to detect its presence is by measuring the scattering signal caused by an active source placed also in the water. Our goal is to numerically investigate the EM scattering process in the presence of a metallic vessel of arbitrary shape placed inside a lossy media.

A frequently occurring geometry for the marine environment is a horizontal stratification with constant conductivity, permittivity and permeability in each layer. The EM scattering from an arbitrary shaped electrical conducting object located in a layered medium is an intricate problem due to the interaction between the boundaries of the media and the scattering object.

To solve the EM scattering problem involving perfectly conducting (PEC) objects we make use of the Method of Moments (MoM) integral equation technique. The scattering fields are expressed as surface integrals on the scattering object surface. The integrands of these integrals consist of scalar products between an unknown surface current density and an electric or magnetic dyadic Green's function for the electric and magnetic fields, respectively. Then the unknown surface current density is obtained from an integral equation derived from the magnetic scattered field representation. The method of moments (MoM) is used to transform the magnetic field integral equation into a linear system of equations solved for the induced electric surface currents. Then the fields produced by the equivalent electric dipoles distributed on the object surface are calculated by taking into account the actual layered structure.

The EM scattering numerical code was written in Fortran. The solution is applied to the investigation of EM scattering by a submarine modelled as a tapered long cylinder plus the tower when is placed in different positions relative to the source and the sensors. It is shown that, by an appropriate design of the experiment, the signal indicating the presence of the target can be increased relative to the signal obtained in its absence.

Résumé

La technique active de détection électromagnétique sous-marine vise la découverte des navires furtifs à coque d'acier (sous-marin ou vaisseau de surface), placés dans une couche horizontale d'eau de mer. On présume que le navire n'a pas de signature acoustique ou électromagnétique et que la seule façon de déceler sa présence est de mesurer la diffusion d'un signal émis par une source immergée. Notre objectif était d'étudier numériquement la diffusion électromagnétique produite par un navire métallique de forme arbitraire placé dans un milieu à perte et stratifié.

Généralement, on peut représenter l'environnement marin comme une série de strates horizontales, caractérisées par une conductivité, une permittivité et une perméabilité constantes. La diffusion électromagnétique d'un objet conducteur de forme arbitraire placé dans un milieu stratifié est un problème difficile, étant donné l'interaction entre les limites du milieu et l'objet diffusant.

Nous avons résolu le problème de la diffusion électromagnétique par des objets parfaitement conducteurs en exploitant la méthode des moments pour résoudre l'équation intégrale. Les champs diffusés sont exprimés par des intégrales de surface, à la surface des objets diffusants. Les fonctions à intégrer sont les produits scalaires d'un courant de surface inconnu par une fonction dyadique de Green, électrique ou magnétique, selon le champ considéré. Ensuite, nous obtenons la densité de courant inconnue, à partir de l'équation intégrale dérivée de la représentation du champ magnétique diffusé. L'application de la méthode des moments permet de transformer l'équation intégrale du champ magnétique en un système d'équations linéaires que l'on résout pour trouver les courants de surface induits. Nous calculons alors les champs produits par les dipôles électriques équivalents distribués à la surface de l'objet, en tenant compte de la structure stratifiée.

Nous avons écrit le programme de simulation de la diffusion électromagnétique en FORTRAN. Nous avons utilisé la solution pour étudier la diffusion électromagnétique par un sous-marin modélisé comme un long cylindre effilé surmonté d'un kiosque, placé dans différentes positions relativement à la source et aux capteurs. Nous montrons grâce à une conception appropriée de l'expérience, que le signal indiquant la présence d'une cible peut être supérieur au signal reçu en son absence.

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Executive summary

Introduction

For several years, the active electromagnetic (EM) detection method has been experimented in our laboratory as a possible surveillance system for surface and submerged vessels. The experiments were motivated by the potential of the electromagnetic active detection systems to outperform the acoustic systems in certain situations. The modern surface and submerged vessels are very quiet acoustically, so that they are difficult to detect by passive acoustic methods. Moreover, in shallow waters and surf zones both passive and active acoustic detection techniques perform poorly due to multiple scattering at the boundaries and high noise level.

The underwater EM active detection technique attempts to reveal a stealth iron-hull vessel (submarine or surface warship) located in a horizontal layer of seawater. It is supposed that the vessel has no acoustic or EM signature and the only way to detect its presence is by measuring the scattering signal caused by an active source placed also in the water. The conducting water layer is situated between a half-space of air and a known number of layers representing sediments of lower electrical conductivity. The electrical conductivity of the metallic hull is at least seven orders of magnitude higher than the conductivity of the surrounding media, so that the vessel could be considered as a perfectly conducting 3-D object. An electric or magnetic source placed in the water creates an EM field that propagates in the layered marine environment and illuminates the vessel, which in turn will generate a scattered signal.

The ability to set up appropriate EM experiments and to enhance the interpretation of the measured signals makes it necessary to use realistic and efficient numerical models. Our goal is to numerically investigate the scattering process in the presence of the metallic vessel. This report presents a mathematical model of the EM scattering caused by a perfectly conducting (PEC) body of arbitrary shape placed inside a lossy-layered media.

Results

To solve the EM scattering problem involving perfectly conducting (PEC) objects in layered media we make use of the Method of Moments (MoM) integral equation technique. The scattering fields are expressed as surface integrals on the scattering object surface. The integrands of these integrals consist of scalar products between an unknown surface current density and an electric or magnetic dyadic Green's function for the electric and magnetic fields, respectively. The dyadic Green's functions are fundamental wave propagation solutions to a certain stratified geometry. In other words, the interaction between the scattering object and the air-seawater and seawater-seabed interfaces is taken into account. Then the unknown surface current density is obtained from an integral equation of the second kind derived from the magnetic scattered field representation. This approach for solving the scattering problem is called the magnetic field integral equation (MFIE). The method of

moments (MoM) is used to transform the magnetic field integral equation (MFIE) into a linear system of equations. The resulting matrix equation is solved for the induced electric surface currents by Gauss elimination. Then the fields produced by the equivalent electric dipoles distributed on the object surface are calculated by taking into account the actual layered structure. The EM scattering numerical code was written in Fortran. The solution is applied to investigate the EM scattering by a submerged submarine when it is placed in different positions relative to the source and the sensors. The measured electric and magnetic fields are composed as the sum of the direct (primary) incoming fields from the source, i.e. the wave propagation fields without any scattering object in the environment, and the scattered (secondary) fields due to the object. It is shown that, by an appropriate design of the experiment, the signal indicating the presence of the target can be increased relative to the signal obtained in its absence.

Significance

The mathematical model of the EM scattering by metallic objects submerged in seawater or buried in the sediment offers useful information for designing the underwater EM active detection (of vessels or mines) experiments and interpreting the experimental data.

Future plans

In the active detection of the vessels, the EM source and sensor are located in the seawater, but a particular advantage of inductive coupling is that it permits the use of EM systems in aircraft as an additional tool to the Magnetic Anomaly Detection (MAD) system.

Because the direct (primary) field is much higher than the secondary field, it is necessary to use measurement techniques to diminish the primary field effect. Such methods were developed and electromagnetic equipment has been widely applied in mineral exploration reconnaissance. For the future, it is intended to verify the applicability of the geophysical electromagnetic methods in underwater active detection and to develop new measurement techniques, in the water or in the air, if necessary.

Birsan M. 2004. Modelling the electromagnetic scattering by 3-D objects in a layered media. DRDC Atlantic TM 2004-246. DRDC Atlantic.

Sommaire

Introduction

Depuis plusieurs années, nous étudions en laboratoire la possibilité d'utiliser la détection électromagnétique active pour surveiller les navires immergés ou en surface. Ces expériences sont motivées par la possibilité que, dans certaines situations, les systèmes de détection électromagnétique active soient supérieurs aux systèmes acoustiques. Étant donné la grande discrétion acoustique des navires modernes — tant en surface ou sous l'eau — il est devenu difficile de les détecter par les méthodes acoustiques passives. En outre, dans les hauts fonds et les zones de déferlement, les techniques acoustiques de détection, actives ou passives, sont inefficaces, à cause des diffusions multiples sur les bords et l'intensité du bruit ambiant.

La technique active de détection électromagnétique sous-marine vise la découverte des navires furtifs à coque d'acier (sous-marin ou vaisseau de surface), placés dans une couche horizontale d'eau de mer. On présume que le navire n'a pas de signature acoustique ou électromagnétique et que la seule façon de déceler sa présence est de mesurer la diffusion d'un signal émis par une source immergée. La couche d'eau conductrice s'étend entre un demi-espace d'air et le lit formé d'un nombre connu de strates de sédiments, dont la conductivité électrique est plus basse. La conductivité électrique d'une coque métallique est, au moins, sept ordres de magnitude plus élevée que celle du milieu ambiant et, ainsi, on peut considérer que le navire est un objet tridimensionnel parfaitement conducteur. Une source électrique ou magnétique placée dans l'eau génère un champ électromagnétique qui se propage dans le milieu marin stratifié et illumine le vaisseau qui diffuse un signal.

Puisque nous pouvons réaliser des expériences électromagnétiques adéquates et accentuer les signaux mesurés pour les interpréter, nous devons utiliser des modèles numériques réalistes et efficaces. Notre objectif était donc d'étudier numériquement la diffusion par un navire métallique. Dans ce rapport, nous présentons un modèle mathématique de la diffusion électromagnétique par un corps parfaitement conducteur, de forme arbitraire, placé dans un milieu à perte et stratifié.

Résultats

Nous avons résolu le problème de la diffusion électromagnétique par des objets parfaitement conducteurs dans un milieu stratifié, en exploitant la méthode des moments pour résoudre l'équation intégrale. Les champs diffusés sont exprimés par des intégrales de surface, à la surface des objets diffusants. Les fonctions à intégrer sont les produits scalaires d'un courant de surface inconnu par une fonction dyadique de Green, électrique ou magnétique, selon le champ considéré. Les fonctions dyadiques de Green sont les solutions fondamentales de propagation dans une géométrie stratifiée donnée. En d'autres termes, il faut considérer l'interaction entre l'objet diffusant et les interfaces air-eau et eau-fond. Ensuite, nous obtenons la densité de courant inconnue, à partir de l'équation intégrale de deuxième espèce, dérivée de la

représentation du champ magnétique diffusé. On appelle équation intégrale du champ magnétique, cette méthode de résolution du problème de diffusion. L'application de la méthode des moments nous permet de transformer l'équation intégrale du champ magnétique en un système d'équations linéaires. Nous utilisons ensuite la méthode d'élimination de Gauss pour résoudre l'équation matricielle résultante pour les courants de surface induits.

Nous calculons alors les champs produits par les dipôles électriques équivalents distribués à la surface de l'objet, en tenant compte de la structure stratifiée. Nous avons écrit le programme de simulation de la diffusion électromagnétique en FORTRAN. La solution est utilisée pour étudier la diffusion électromagnétique par un sous-marin immergé, placé dans différentes positions relativement à la source et aux capteurs. Les champs électriques et magnétiques mesurés sont la résultante des champs directs (primaires) émis par la source — soit les champs de propagation des ondes dans un environnement ne comportant pas d'objet diffusant — et des champs diffusés par l'objet (secondaires). Nous montrons grâce à une conception appropriée de l'expérience, que le signal indiquant la présence d'une cible peut être supérieur au signal reçu en son absence.

Portée

Le modèle mathématique de diffusion électromagnétique par des objets métalliques plongés dans l'eau de mer ou enfouis dans les sédiments fournit des informations utiles pour la conception des expériences de détection électromagnétique active sous-marine (de navires ou de mines) et pour interpréter les données expérimentales.

Futures recherches

Pour la détection active des navires, la source électromagnétique et les capteurs sont situés dans l'eau de mer. Toutefois, le couplage inductif présente l'avantage supplémentaire de permettre l'utilisation de systèmes électromagnétiques aéroportés comme outil additionnel au système de détection d'anomalie magnétique.

Puisque le champ direct (primaire) est beaucoup plus intense que le champ secondaire, il est nécessaire d'utiliser des techniques de mesure permettant de réduire l'effet du champ primaire. Ces méthodes ont déjà été mises au point et on a largement utilisé l'équipement électromagnétique issu de ces travaux pour la prospection minière. À l'avenir, nous prévoyons expérimenter des méthodes électromagnétiques géophysiques pour la détection sous-marine active et la mise au point de nouvelles techniques de mesure, sous l'eau ou dans l'air, au besoin.

Birsan M. 2004. *Modelling the electromagnetic scattering by 3-D objects in a layered media*. (Modélisation de la diffusion électromagnétique par des objets tridimensionnels placés dans un milieu stratifié) RDDC Atlantique TM 2004-246. RDDC Atlantique.

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1. Introduction

The detection and classification of submerged objects in seawater is mainly performed using hydro-acoustic or electromagnetic methods. These methods can further be divided into passive and active methods. A passive system consists of sensors that detect either the sounds emitted by the submerged objects or their electromagnetic signature. An active system consists of both sources and sensors. The sources radiate acoustic or electromagnetic energy towards the object and the sensors are designed to detect any reflected energy.

For several years, the active electromagnetic (EM) detection method has been experimented in our laboratory as a possible surveillance system. The experiments were motivated by the potential of the electromagnetic active detection systems to outperform the acoustic systems in certain situations. The modern surface and submerged vessels are very quiet acoustically, so that they are difficult to be detected by passive acoustic methods. Moreover, in shallow waters and surf zones both passive and active acoustic detection techniques perform poorly due to multiple scattering at the boundaries and high noise level. It is also assumed that, in the future, the vessels will be equipped with degaussing and anti-corrosion systems designed to completely cancel their magnetic and electric signatures.

The active electromagnetic (EM) detection of the surface (partially submerged) and submerged vessels in the seawater or of the buried/partially buried objects in the sediment is based on the measurement of the response (scattered) signal from the metallic object due to an EM source. The method involves the propagation of time-varying, low frequency electromagnetic fields in and over the ocean. The detector receives its signal by induction. The measured total electric and magnetic fields are composed as the sum of the direct incoming fields from the source, i.e. the wave propagation fields without any scattering object in the environment, and the scattered fields due to the object. In the active detection of the vessels, the EM source and sensor are located in the seawater, but a particular advantage of the inductive coupling is that it permits the use of EM systems in aircraft. Airborne electromagnetic in combination with magnetic equipment has been widely applied in mineral exploration reconnaissance, so that it could be an additional tool to the Magnetic Anomaly Detection (MAD) system.

The ability to set up appropriate EM experiments and to enhance the interpretation of the measured signals makes it necessary to use realistic and efficient numerical models. It is the purpose of this report to present a mathematical model of the EM scattering caused by a perfectly conducting (PEC) body of arbitrary shape placed inside a lossy-layered media.

To solve the EM scattering problem involving perfectly conducting (PEC) objects we make use of the Method of Moments (MoM) integral equation technique. The methodology used in this report follows closely the one used in the well-known code NEC (Numerical Electromagnetic Code) developed at the Lawrence Livermore Laboratory for the solution of the EM scattering and radiation problems involving objects of arbitrary shape in free space. The NEC Fortran code is available in the public domain. However, for the underwater active detection applications, it is necessary to formulate the scattering problem for an arbitrary shaped PEC object located in a layered media, which is an intricate scattering problem. The difficulty of such a problem is due to the interaction between the boundaries of the media and the scattering object.

A frequently occurring geometry for the marine environment is a horizontal stratification with constant conductivity, permittivity and permeability in each layer. Examples of papers dealing with electromagnetic very low frequency (VLF) scattering and wave propagation in such environmental configurations are references [1-6]. The mathematical techniques used for the scattering part of the problem are mostly various integral equation (IE) formulations with different method of moments (MoM) concepts, [2, 3, 4, 6]. There are also some hybrid techniques where the integral equation and the finite elements (FE) method are combined, [7, 8]. The FE method is used to model an inhomogeneous scattering object and the integral equation technique for taking care of the surroundings to the object. The two methods are linked together through the boundary conditions at a circumscribing surface to the scattering object. Other methods that are useful for modelling inhomogeneous objects and non-plane stratified environments are the finite difference time domain (FDTD) method [1], and FE methods for both the scattering object and the surrounding environment [9]. An efficient method for modelling the scattering by a heterogeneous collection of spatially separated objects is a modified recursive T-matrix algorithm given in [10].

The underwater EM active detection technique attempts to reveal a stealth iron-hull vessel (submarine or surface warship) located in a horizontal layer of seawater. It is supposed that the vessel has no EM signature and the only way to detect its presence is by measuring the scattering signal caused by an active source placed also in the water. The conducting water layer is situated between a half-space of air and a known number of layers representing sediments of lower electrical conductivity. The electrical conductivity of the metallic hull is about seven orders of magnitude higher than the conductivity of the surrounding media, so that the vessel could be considered as a perfect conducting 3-D object. The paint or other insulating materials on the hull do not affect the perfectly conducting (PEC) assumption because the wavelength of the EM signal is much bigger than the thickness of the insulation. An electric or magnetic source placed in the water creates an EM field that propagates in the layered marine environment and illuminates the vessel, which in turn will generate a scattered signal. Our goal is to numerically investigate the scattering process from the vessel. The information is useful in designing the EM active detection experiment and interpreting the experimental data.

Pure EM-wave propagation in horizontally stratified conducting media without object scattering is treated in [11]. The sources are elementary vertical and horizontal current or magnetic dipoles placed in an arbitrary layer of a N-layers configuration. The quasi-static approximation given in [12] is used.

The scattering object is a smooth perfectly conducting 3-D object, which can be placed in any of the layers of an arbitrary horizontally stratified dissipative environment. The surface of the object is modelled by perfectly conducting flat surface patches.

The scattering fields are expressed as surface integrals on the scattering object surface. The integrands of these integrals consist of scalar products between an unknown surface current density and an electric or magnetic dyadic Green's function for the electric and magnetic fields, respectively. The dyadic Green's functions are fundamental wave propagation solutions to a certain stratified geometry. In other words, the interaction between the scattering object and the air-seawater and seawater-seabed interfaces is taken into account. The N-layers code is utilised to construct the dyadic Green's functions when the geometry of the environment is horizontally stratified in more than two conducting layers. Then the unknown surface current density is obtained from an integral equation of the second kind derived from the magnetic scattered field representation. This approach for solving the scattering problem is called the magnetic field integral equation (MFIE).

The integral equation approach is best suited to structures with dimensions up to several wavelengths. When the structure size is increased relative to wavelength, standard high-frequency approximations such as physical optics or geometric theory of diffraction may be more suitable approaches. For the underwater active detection applications, the source frequency is low enough, so that the wavelength is usually bigger than the largest dimension of the object to be detected.

The method of moments (MoM) is used to transform the magnetic field integral equation (MFIE) into a linear system of equations. The resulting matrix equation is solved for the induced electric surface currents by Gauss elimination. Next the fields produced by the equivalent electric dipoles distributed on the object surface are calculated by taking into account the actual layered structure. The scattering numerical code was written in Fortran. The solution is applied to the investigation of EM scattering by a submarine modelled as a tapered long cylinder plus the tower when is placed in different positions relative to the source and the sensors.

2. The formulation of the problem

Consider a smooth perfect conducting (PEC) object submerged in a horizontal layer of seawater of depth d_w (**Figure 1**). The X and Y directions denote the horizontal plane. This is the plane in which the structure is uniform in its electromagnetic parameters. The Z direction is the vertical direction pointing downwards in which the structure varies in its properties. The origin of this Cartesian reference frame is located on the interface of air and seawater. A layered conducting medium occupies the half-space $Z > 0$ of the rectangular coordinate system (X, Y, Z) and has the conductivity σ_1 for $0 < Z < d_w$, σ_2 for $d_w < Z < d_w+d_s$, where d_s is the sediment thickness, and so on. The region $Z < 0$ is taken to be free-space. The position of the current source has the coordinates $X = Y = 0$, $Z = h_d$ $(0 < h_d < d_w)$. The forcing current has a sinusoidal temporal dependence, so that the time dependence factor $\exp(i\omega t)$ is suppressed throughout.

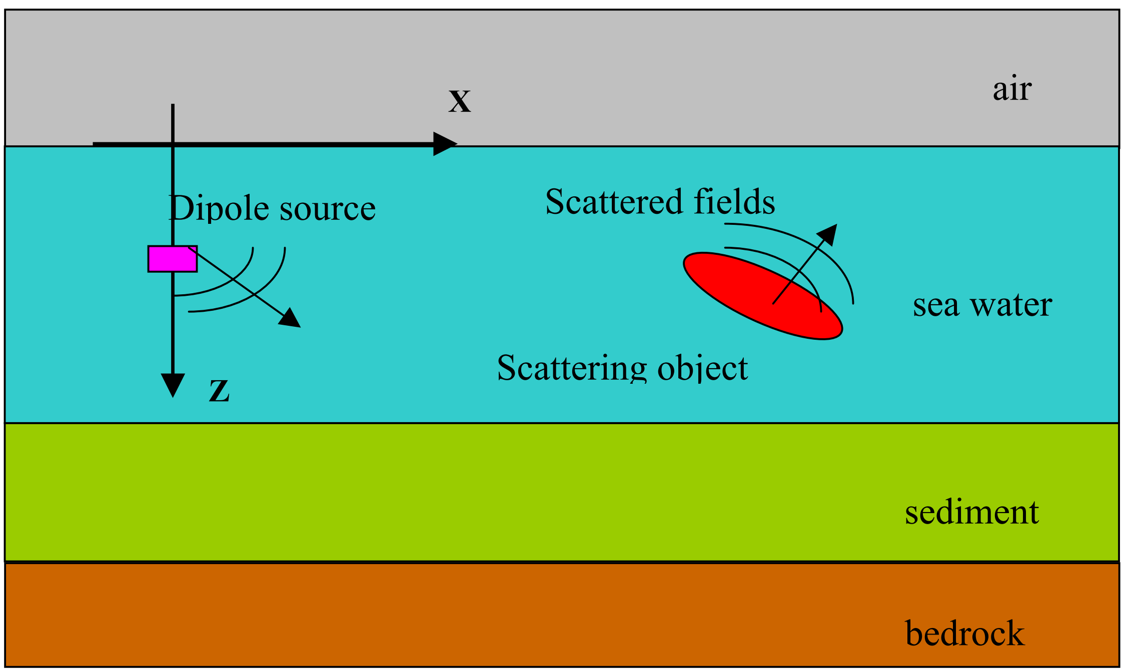


Figure 1. *Geometry of the EM scattering problem in a marine environment.*

The wave number k is given by $k = \sqrt{\omega\mu_0(\omega\varepsilon + i\sigma)}$, where ω is the angular frequency, ε the permittivity and σ the conductivity, and it is assumed that all layers are non-magnetic, i.e. the permeability is μ_0 everywhere. The much higher conductivity of seawater compare to air or sediment leads to a much greater complex wave number for EM waves in seawater. At low frequencies, the wave number in water is approximated as:

$$k_1 = \beta_1 + i\alpha_1 \approx (i\omega\mu_0\sigma_1)^{1/2} = (1+i)(\omega\mu_0\sigma_1/2)^{1/2} \tag{1}$$

The associated wavelength $\lambda_1 = 2\pi/\beta_1$ is much shorter than that in the air at the same frequency. It follows that a much lower frequency must be used in order to formulate the scattering problem in terms of integral equations valid when the characteristic geometric dimension of the object is smaller than the operating wavelength. For example, if the scattering object is a submarine with a length of 50m, the frequency must be smaller than 225 Hz (λ_1 = 105m for seawater with σ_1 = 4S/m).

The wave equations for the electric and magnetic fields $\mathbf{E}_j$ and $\mathbf{H}_j$, in layer j (j = 0, 1, 2, 3), are derived from the Maxwell's equations for time-harmonic fields:

$$\begin{aligned} \nabla \times \mathbf{E}_j &= i\omega\mu_0 \mathbf{H}_j \\ \nabla \times \mathbf{H}_j &= \sigma_j \mathbf{E}_j + \mathbf{J}_j + \nabla \times \mathbf{M}_j \end{aligned} \tag{2}$$

where $\mathbf{J}_j$ and ∇ x $\mathbf{M}_j$ represent the external electric or magnetic source, and the displacement currents were neglected. The boundary conditions require that the magnetic field and the tangential component of the electric field are continuous at each interface (j = 0, 1, 2):

$$\hat{\mathbf{z}} \times \left(\mathbf{E}_j - \mathbf{E}_{j+1}\right) = 0, \qquad \hat{\mathbf{z}} \times \left(\mathbf{H}_j - \mathbf{H}_{j+1}\right) = 0 \tag{3}$$

Pure EM-wave propagation in horizontally stratified conducting media without object scattering is treated in [11]. The sources are elementary vertical and horizontal current or magnetic dipoles placed within one layer of a N-layers configuration. The quasi-static approximation given in [12] is used.

The total electric ***E***- and magnetic ***H***-fields at the observation point are the sums of the incident (primary) fields from the source and the scattered (secondary) fields from the PEC 3-D object, that is $\mathbf{E} = \mathbf{E}^i + \mathbf{E}^s$ and $\boldsymbol{H} = \boldsymbol{H}^i + \boldsymbol{H}^s$. The incident $\boldsymbol{E}^i$- and $\boldsymbol{H}^i$-fields are the wave propagation solutions satisfying the prescribed horizontally stratified geometry without the scattering object. The scattering contributions from the object, $\boldsymbol{E}^s$ and $\boldsymbol{H}^s$, also satisfy the N-layers geometry. This means that all multiple scattering effects are taken into account.

In the integral equation formulation, the scattered fields $\boldsymbol{E}^s$ and $\boldsymbol{H}^s$ are expressed as integral representations over the scattering object surface. For a perfect conducting object the representations are:

$$
\begin{aligned}
\mathbf{E}^s(\mathbf{r}) &= -i\omega\mu_0 \int_S \mathbf{G}_\mathbf{e}(\mathbf{r},\mathbf{r}')\cdot \mathbf{J}_S(\mathbf{r}')\,dS(\mathbf{r}') \\
\mathbf{H}^s(\mathbf{r}) &= -\int_S \mathbf{G}_m(\mathbf{r},\mathbf{r}')\cdot \mathbf{J}_S(\mathbf{r}')\,dS(\mathbf{r}')
\end{aligned}
\tag{4}
$$

where $\mathbf{J}_S(\mathbf{r}')$ is the surface current density producing the scattering fields. The electric and magnetic dyadic Green's functions $\boldsymbol{G}_e(\boldsymbol{r},\boldsymbol{r}')$ and $\boldsymbol{G}_m(\boldsymbol{r},\boldsymbol{r}')$ are 3 x 3 matrices where the columns are the $\boldsymbol{E}(\boldsymbol{r})$- and $\boldsymbol{H}(\boldsymbol{r})$-fields, respectively, from normalised electric current dipoles in three mutually perpendicular directions at the point $\boldsymbol{r}'$ in the selected stratified geometry. This means that the expressions in (4) are also solutions to that geometry. The vectors $\mathbf{r}$ and $\boldsymbol{r}'$ may position the observation point and the source in the same layer or in different layers.

If the surface current $\mathbf{J}_S(\mathbf{r}')$ is induced by an external incident field, $\boldsymbol{H}^i$, then the total magnetic field just inside the PEC object surface is zero:

$$
\mathbf{H}^i(\mathbf{r}) + \mathbf{H}^s(\mathbf{r}) = 0 \tag{5}
$$

for $\mathbf{r}$ just inside the surface of the PEC object.

The unknown surface current density $\mathbf{J}_S(\mathbf{r})$ on the scattering object surface may be calculated from an integral equation of the second kind. This integral equation is obtained by operating with the outward unit normal $\mathbf{n}(\mathbf{r})$ from the left in equation (5) and substituting the $\boldsymbol{H}^s$-field representation from equation (4). Letting $\boldsymbol{r} \to S$ from inside the scattering object along the normal, the surface component of equation (4) is:

$$
-\frac{1}{2}\mathbf{J}_S(\mathbf{r}) + \int_S \mathbf{n}(\mathbf{r}) \times \left(\mathbf{G}_m(\mathbf{r},\mathbf{r}')\cdot \mathbf{J}_S(\mathbf{r}')\right) dS(\mathbf{r}') = -\mathbf{n}(\mathbf{r}) \times \mathbf{H}^i(\mathbf{r}) \quad , \quad \mathbf{r} \in S \tag{6}
$$

provided that the surface S is smooth.

The dyadic $\mathbf{G}_\mathrm{m}$ contains the three magnetic field solutions to three volume sources that are normalized infinitesimal current dipoles in three mutual perpendicular directions located at **r**'. The wave equation for the dyadic Green's function with the source placed in water (j = 1) is:

$$
\nabla \times \nabla \times \mathbf{G}_{mj}(\mathbf{r},\mathbf{r}') - k_j^2\, \mathbf{G}_{mj}(\mathbf{r},\mathbf{r}') = \nabla \times \left[\mathbf{I}\,\delta(\mathbf{r}-\mathbf{r}')\right]\delta_{1j}
$$

where **I** is the unit diagonal dyadic and δ(**r**-**r'**) is the delta Dirac function. The boundary conditions at the region interfaces for $\mathbf{G}_m$ are the same as for the **H** field.

The vector $\mathbf{J}_S(\mathbf{r}')$ is tangential to the surface S. It can therefore be decomposed as $\mathbf{J}_S(\mathbf{r}') = \mathbf{e}_1(\mathbf{r}')J_1(\mathbf{r}') + \mathbf{e}_2(\mathbf{r}')J_2(\mathbf{r}')$ where $\mathbf{e}_1(\mathbf{r}')$ and $\mathbf{e}_2(\mathbf{r}')$ are two orthogonal unit tangential vectors at the point $\boldsymbol{r}'$ on *S*, and $\mathbf{e}_1(\mathbf{r}') \times \mathbf{e}_2(\mathbf{r}') = \mathbf{n}(\mathbf{r}')$. The vector integral equation (6) is then projected onto these tangential vectors at the point ***r'*** to obtain two scalar equations. By using the identity $\mathbf{u} \cdot (\mathbf{v} \times \mathbf{w}) = (\mathbf{u} \times \mathbf{v}) \cdot \mathbf{w}$ and noting that $\mathbf{e}_1(\mathbf{r}') \times \mathbf{n}(\mathbf{r}') = -\mathbf{e}_2(\mathbf{r}')$ and $\mathbf{e}_2(\mathbf{r}') \times \mathbf{n}(\mathbf{r}') = \mathbf{e}_1(\mathbf{r}')$, the scalar equations are:

$$\begin{aligned}
-\frac{1}{2}\mathbf{e}_1(\mathbf{r}) \cdot \mathbf{J}_S(\mathbf{r}) - \int_S \mathbf{e}_2(\mathbf{r}) \cdot \left(\mathbf{G}_m(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_S(\mathbf{r}')\right) dS(\mathbf{r}') &= \mathbf{e}_2(\mathbf{r}) \cdot \mathbf{H}^i(\mathbf{r}) \\
\frac{1}{2}\mathbf{e}_2(\mathbf{r}) \cdot \mathbf{J}_S(\mathbf{r}) - \int_S \mathbf{e}_1(\mathbf{r}) \cdot \left(\mathbf{G}_m(\mathbf{r},\mathbf{r}') \cdot \mathbf{J}_S(\mathbf{r}')\right) dS(\mathbf{r}') &= \mathbf{e}_1(\mathbf{r}) \cdot \mathbf{H}^i(\mathbf{r})
\end{aligned} \tag{7}$$

These two equations are sufficient because there is no normal component of the surface current.

The system of coupled scalar equations (7) is solved by the Method of Moments approach. This means that the surface is discretized and that the unknown components J_1 and J_2 are expanded in a suitable set of basis functions. In this way, the integral equations are converted into a system of linear equations where the expansion coefficients are the unknown.

3. The method of moments (MoM)

Equations (7) have the form: $L(g) = h$, where L is a known linear operator, h is a known excitation function, and g is the response function. For equations (7), L is an integral operator. The objective here is to determine g when L and h are specified. While the problem is often intractable in closed form, the linearity of the operator L makes a numerical solution possible. Such a solution is provided by the Method of Moments (MoM) where the unknown response, g, is represented as a linear combination of known basis or expansion functions, $g_m(u)$:

$$g(u) = \sum_{m=1}^{M} \alpha_m \, g_m(u) \tag{8}$$

The linearity of the operator L makes it possible to write:

$$\sum_{m=1}^{M} \alpha_m \, L(g_m) = h \tag{9}$$

For finite M this equality is usually approximate. The choice of the basis functions is important for the efficiency and the accuracy of the solution. They are selected so that each $L(g_n)$ can be evaluated conveniently, preferably in closed form.

Equation (9) has M unknowns. To solve for the M unknowns, a set of M equations are obtained by introducing the testing or weighting functions, w_n, and taking the inner product (an integration over the structure surface in this case) of (9):

$$\sum_{m=1}^{M} \alpha_m \langle w_n, L(g_m) \rangle = \langle w_n, h \rangle, \quad m = 1,2,3,\ldots,M \tag{10}$$

The weighting functions must be linearly independent, so that the M equations (10) will be linearly independent. Also their selection is based on the minimization of the computational requirements to evaluate the inner product.

The system of equations (10) can be written in matrix form:

$$\begin{gathered} [G][A] = [H] \\ G_{mn} = \langle w_m, L(g_n) \rangle; \quad A_m = \alpha_m; \quad H_n = \langle w_n, h \rangle \end{gathered} \tag{11}$$

that could be solved for [A], if [G] is non-singular, using classical routines (for example, LU decomposition and forward-backward substitution are used in the present calculation).

Various choices of basis and weighting functions are possible. When the two functions are identical, $w_m = g_m$, the procedure is known as Galerkin's method. In the present code, the weighting function is different from the basic function. The weighting functions are a set of delta functions:

$$w_m(\mathbf{r}) = \delta(\mathbf{r} - \mathbf{r}_m) \tag{12}$$

where $\{\mathbf{r}_m\}$ is a set of points on the conducting surface. The result is that the integral equations are projected onto Dirac delta functions at the points of the discretized surface. The method is referred as the collocation or point matching method.

The basis functions chosen to expand the surface current on each patch is a set of pulse functions. This selection simplifies the evaluation of the inner product integral and ensures that the matrix [G] is well conditioned. The pulse function expansion for a number of P patches is:

$$\mathbf{J}_S(\mathbf{r}) = \sum_{j=1}^{P} \left[J_{1j}\mathbf{e}_{1j}(\mathbf{r}_j) + J_{2j}\mathbf{e}_{2j}(\mathbf{r}_j) \right] v_j(\mathbf{r}) \tag{13}$$

where $\mathbf{r}_j$ is the point matching at the centre of patch number j, and $v_j(\mathbf{r}) = 1$ for $\mathbf{r}$ on patch j and 0 otherwise. The current expansion substituted into (7) leads to a linear set of equations that can be written in the matrix form (11) from where the unknown expansion coefficients J_{1j} and J_{2j} representing the average current density on the surface of the patch are determined.

The matrix element G_{mn} represents the tangential magnetic field component at patch m due to a surface current pulse on patch n. The pulse is in the direction $\mathbf{e}_1$ when n is odd, and in the direction $\mathbf{e}_2$ when n is even. For m = n, the contribution to the vector product on the flat surface is given only by the images of the patch current created on the boundaries, which is added to the coefficient of $\mathbf{J}_S(\mathbf{r})$ in equations (7) that is $\pm 1/2$. In a homogeneous space the surface integral is zero since the vector product is zero. However, $G_{mm} = \pm 1/2$ in this case.

4. Surface modeling

The surface of a perfectly conducting (PEC) object is modelled by means of multiple flat surface patches chosen in a manner to cover completely the surface to be modelled. Thus the surface is subdivided into a reasonably number of patches conforming as closely as possible to both the flat and curved surfaces. The modelled surface must be closed since the patches only model the side of the surface from which the normal is directed outward. The shape of an elementary patch does not affect the solution since there is no integration over the patch. The program computes the surface current in the centre of each patch along the orthogonal unit vectors $\mathbf{e}_1(\mathbf{r})$ and $\mathbf{e}_2(\mathbf{r})$, which are tangent to the surface. These current components are essentially electric dipoles that radiate in the presence of the interfaces of the stratified structure (4).

Although an elementary patch may be defined using a shape (square, rectangular, triangle) on the input of the program, the actual parameters defining a surface patch are the Cartesian coordinates of the patch centre, the components of the outward directed unit normal vector and the patch area.

As mentioned before, the particularities of the integral equation method make a model useable within a frequency band. Patch size measured in wavelengths is very important for accuracy of the results. A minimum of about 25 patches should be used per square wavelength of surface area, with the maximum size for an individual patch about 0.04 square wavelengths.

The optimum model for a structure can be estimated by varying the patch density and observing the effect on the results. Some dependence of results on segmentation will always be found. A large dependence, however, would indicate that the solution has not converged and more patches should be used.

5. Numerical examples

To simulate the electromagnetic response of a 3-D PEC body in a layered media, the algorithm based on the Method of Moments integral equation was implemented in a numerical code written in Fortran. The code was tested against the NEC code for the particular case of the free space (the only capability of the NEC code). However, in the present code the dyadic Green's functions were calculated for a stratified media where the boundaries were placed far away from the source, sensors and scattering object to minimize their influence. The results obtained from the present code and from the NEC code were identical (errors in the fifth digit).

The validity of the program was also checked by comparing results obtained for the case of an infinite long buried horizontal cylinder excited by a horizontal line source of current above the surface of a uniform half-space and parallel to the axis of the buried cylinder. Ogunade [13] analyzed this 2-D problem and obtained a numerical solution from an extension of Dyakonov [14] analytical solution. The approximate solution offered by Ogunade [13] was obtained by truncating the analytical solution to a finite number of terms.

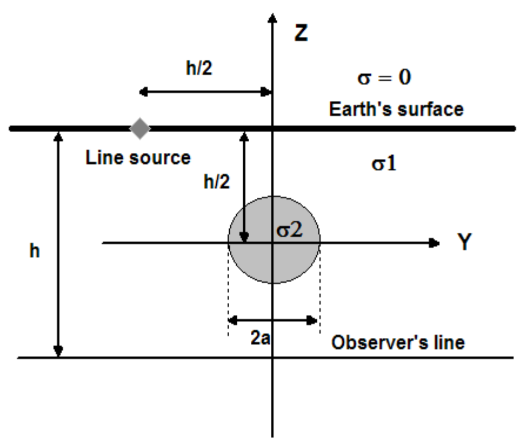


Figure 2. Geometry of the 2-D buried cylinder test problem (Ogunade [13]).

We refer to Figure 2 for the geometry of the test example. An infinite long circular cylinder with radius 'a' and conductivity σ_2 is embedded in a half-space conducting media having the conductivity σ_1. The free space has zero conductivity. The cylinder is oriented with its axis along the X-axis. The calculation was made for the symmetric case where the infinite current carrying wire is located at $y_L = z_L = -h/2$. The measurable quantities are the amplitude and phase of the ratio of horizontal to vertical magnetic fields, Hy/Hz, which are presented in figures 3a and 3b. The figures are defined in terms of numerical distances $H = h\sqrt{\omega\mu_0\sigma_1}$, $A = a\sqrt{\omega\mu_0\sigma_1}$, Y = y/h and conductivity contrast $K = \sigma_2/\sigma_1$. In figures 3a and 3b the numerical parameters are H = 0.1, A = 0.01, and $K = 10^7$. It was considered that the values of σ_1 = 1S/m and σ_2 = 10^7 S/m will offer a good approximation for a perfectly conducting cylinder placed in a lossy media. The agreement between the two solutions is good considering that only 5 terms were used in the truncated analytical solution and that the coupling between modes is neglected (zero non-diagonal terms).

An attempt to reproduce the scattering results presented in the Swedish FOA report [15] for a PEC object in a layered media generated differences of about 15%, which could be explained by the differences in solving for the surface currents in the two codes.

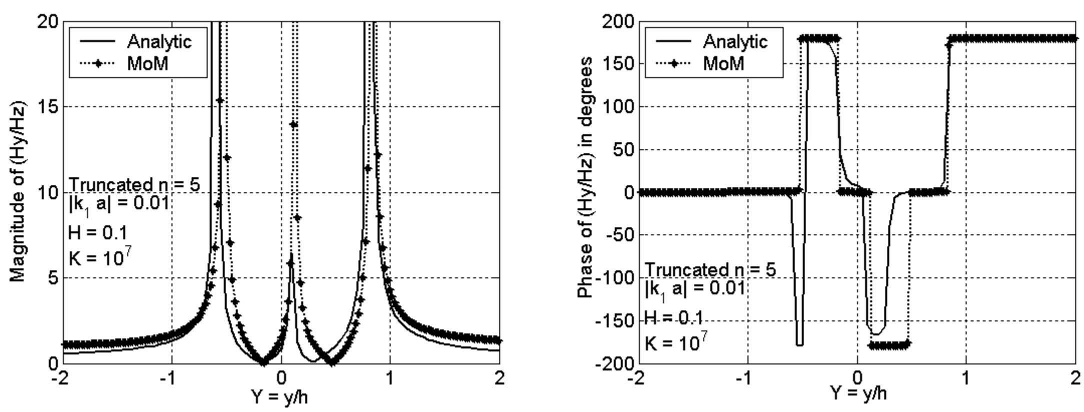


Figure 3. *Numerical and analytical solutions of the 2-D buried cylinder.*

The scattering calculation was applied to investigate the possibility to detect a submerged submarine illuminated by an electric source placed on the sea bottom. The source, which is a 100m long insulated wire with bare ends, carries 10A sine wave current with a constant frequency of 25Hz. The receiver is a 100m long electric field sensor also placed on the sea bottom.

The submarine is modeled with a horizontal cylinder 50m long, 5m in diameter, and has a tower attached. It is submerged at 10m depth, which represent the distance between the central axis of the (cylinder) submarine and the water level. The surface of the submarine was modeled with 678 patches, as illustrated in Figure 4 where half of the surface is presented. By increasing the number of patches to 1278, the solution changes in its fourth digit, but the computation time doubled from 1 to 2 hours on a 2.2 GHz Pentium 4 computer. Integration of the tensor Green's functions for the matrix elements and the scattering fields is the most time-consuming part of our routine.

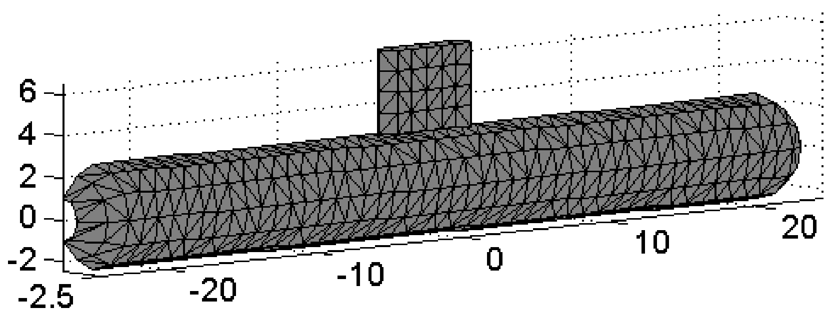
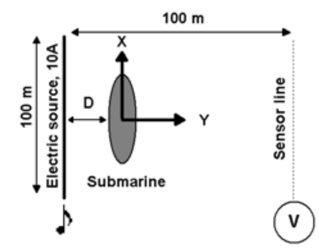
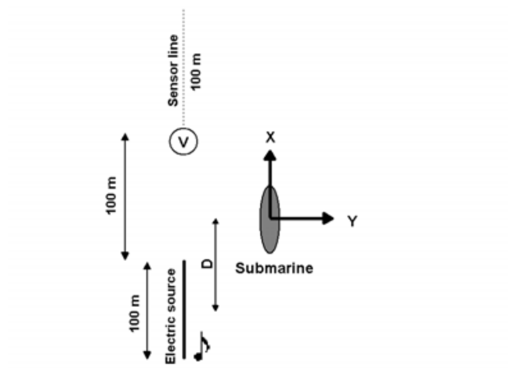


Figure 4. *Half of the submarine surface modeled with 678 PEC patches.*

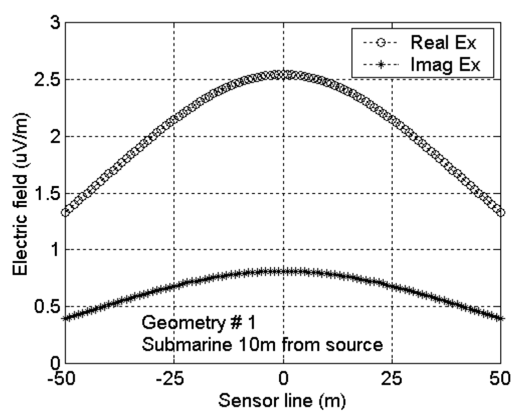
Two geometries were considered, as illustrated in figures 5a and 5b: the submarine is placed parallel with both the source and sensor lines, but the position of the sensor relative to the source is different. In the first geometry (5a), the source and the sensor lines are parallel at 100m separation distance. In the second geometry, the source and the sensor are placed on the same line and they are also 100m separated. For both geometries the water depth was 50m with a conductivity of 3S/m. The sediment layer has the height and conductivity of 2m and 0.03S/m respectively, and the infinite rock bottom has the conductivity of 0.001S/m.

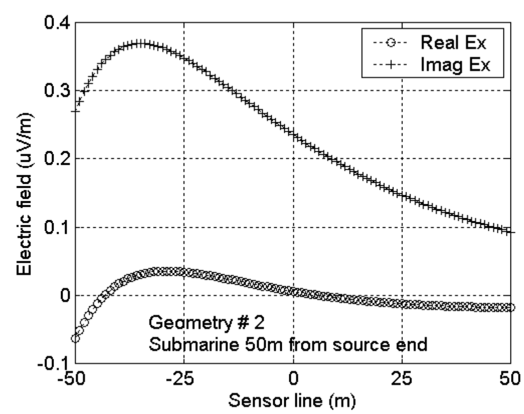
5a. 5b.



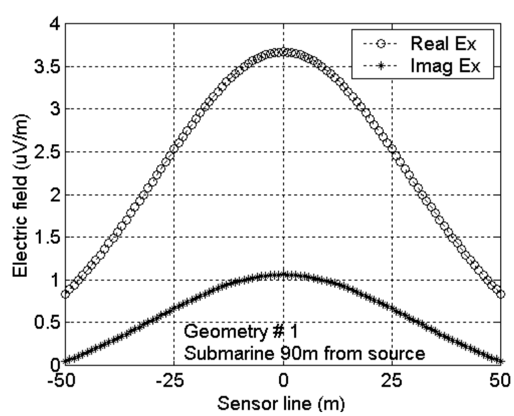


5c. 5d.





5e. 5f.



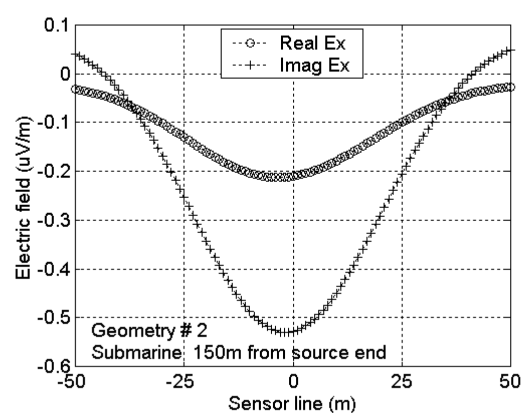


Figure 5. *The position of the submarine in two geometries and the scattering electric field.*

Figures 5c to 5f presents the scattered electric field from the submarine along the sensor line for the two geometries. The measured voltage is calculated by integration along the sensor line and the results are shown in Table 1. In this table are also presented the amplitude and phase of the voltage produced by the direct field (in the absence of the submarine).

The idea of the active detection experiment is to differentiate between the signal measured in the absence of the target (incident or primary fields) and the signal with the target present (primary plus secondary fields). The magnitude of the secondary field is in general very small in comparison to the magnitude of the primary field as it is shown in Table 1. For this reason, one tries to maximize the ratio of secondary to primary fields by choosing an appropriate geometry for experiment.

Table 1. *Direct and scattered voltages obtained on 100m sensor line at 25Hz*

GEOMETRY	V_{direct} (μV)	$V_{scattered}$ (μV)	RATIO (%)
Geo #1, D = 10m	8.878e+3 ∠-176.3°	219.15 ∠17.5°	2.47
Geo #1, D = 50m	8.878e+3 ∠-176.3°	253.09 ∠14.4°	2.85
Geo #1, D = 90m	8.878e+3 ∠-176.3°	217.35 ∠17.3°	2.44
Geo #2, D = 0m	1.473e+3 ∠47.2°	27.27 ∠-116.1°	1.85
Geo #2, D = 100m	1.473e+3 ∠47.2°	23.83 ∠ -90.6°	1.61
Geo #2, D = 200m	1.473e+3 ∠47.2°	26.74 ∠-116.4°	1.81

6. Conclusions

A numerical method was developed for determining the low frequency response of perfectly conducting (PEC) submerged or buried 3-D objects due to an electric or magnetic source. Both the scattering object and the source are located in a layered media. The surface of the object is partitioned into small flat patches. Each patch is defined by its centre and the surface normal with respect to a known coordinate system. The scattering problem is formulated in terms of the magnetic field integral equation (MFIE). The magnetic Green's function appearing in this equation was calculated for a layered medium. Then the Method of Moments is used to transform the integral equation into a matrix equation. We wish to point out that the matrix fill time, not the available computer memory, is the overriding factor that puts practical limits on the size of objects that can be analysed by the technique presented here.

The total measurable electric field was separated into two terms: (a) the direct (primary) field, which is the field as if the scattering object were absent, and (b) the anomalous (secondary) field, which represented the presence of the object. The calculations we have shown, in addition to verifying our numerical solution, indicate that object response is strongly influenced by the presence of layering. Results were presented for a target located in a conducting layer of seawater. The scattered EM field is strongly dependent on the orientation of the vessel with respect to the source and receiver. However, the scattered intensity is typically a few percent of the direct field. For a good detection one needs to maximize the ratio of secondary field to secondary plus primary fields, which could be achieved by an appropriate setting of experiment.

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List of symbols/abbreviations/acronyms/initialisms

DND	**Department of National Defence**
EM	**Electromagnetic**
PEC	**Perfectly conducting**

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The underwater electromagnetic (EM) active detection technique attempts to reveal a stealth iron-hull vessel (submarine or surface warship) located in a horizontal layer of seawater. Our goal is to numerically investigate the EM scattering process in the presence of a metallic vessel of arbitrary shape placed inside a lossy media. To solve the EM scattering problem involving perfectly conducting (PEC) objects we make use of the Method of Moments (MoM) integral equation technique. The EM scattering numerical code was written in Fortran. The solution is applied to the investigation of EM scattering by a submarine modelled as a tapered long cylinder plus the tower when is placed in different positions relative to the source and the sensors. It is shown that, by an appropriate design of the experiment, the signal indicating the presence of the target can be increased relative to the signal obtained in its absence.

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electromagnetic scattering, layered lossy media, active vessel detection, method of moments

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